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To: D. Mills
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CORALL - EXPERT SYSTEM FOR DIAGNOSIS OF CORROSION DAMAGES IN THERMAL POWER GENERATING STATIONS

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CORALL expert system package was developed for use by electric utility and power plant personnel during investigation into the cause of thermal power plant corrosion damage. It is intended to assist their efforts to recognize and identify a basic cause of the damage under investigation. The program guides the user to the most likely damage mechanism by asking simple questions, answers to which can be obtained by determining the type of power plant, damage location, type of fuel, type of metal and from visual inspection of the damaged component.

For the first time, decades of accumulated knowledge, expertise and experience of the builders and operators of power generating stations are available in microcomputer accessible form. In a matter of seconds a damage mechanism can be diagnosed with the same confidence. Use of CORALL does not eliminate the need for a thorough metallurgical analysis during the failure investigation. CORALL is based on reliable information published in the public domain and accepted by the practising experts in the area of thermal power plant corrosion damage analysis.

The CORALL expert system package is designed for ease of use, and no previous computer experience or computer programming knowledge is required.

1.0 INTRODUCTION

Expert systems are computer programs that use knowledge and inference procedures to mimic the deductive reasoning used by human experts. An expert system is a form of artificial intelligence which can be used for diagnosis, monitoring, analyzing, consulting, designing, and many other applications.

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Thermal power generating stations consist of many complex systems. Due to rising costs of equipment downtime, replacement materials, and maintenance personnel, it is necessary to improve efficiency of the process equipment problem analysis and resolution. The use of expert systems can in a significant way contribute toward this objective.

Since the degradation of primary equipment components due to corrosion is the single largest source of forced outages in thermal power generating stations, it is advantageous to have an expert system which can assist in recognizing and identifying basic causes of corrosion damage. It is essential to correctly identify the damage mechanism/cause so the root cause for a failure can be established and proper ameliorative measures taken.

The correct identification of damage mechanisms/causes is a complex process which may include many individuals, institutions, etc. Technical specialists in metallurgy, chemistry, combustion and power plant design frequently cooperate with the station staff in a failure investigation. These individuals rely on personal experience and a large amount of reports, theories, studies, private communications and investigations concerning the different failure modes and mechanisms. As a result of many years of serious effort by the utility companies and manufacturers to mitigate the problem of failures due to corrosion, information exists which make possible correct identification of all routine failure mechanisms which occur in currently operating systems. It is believed that proper dissemination of this knowledge and future findings will contribute to fewer incidents of failures.

An expert system package, CORALL, was developed for use by electric utility and power plant personnel to assist their efforts to recognize and identify a basic damage mechanism during investigations into the cause of corrosion damage. The program guides the user to the most likely damage mechanism by asking simple questions, answers to which can be obtained by determining the type of plant, type of fuel, failure location, type of metal, and from visual inspection of the damaged component. The CORALL expert system package is designed for ease of use, and no previous computer experience or computer programming knowledge is required.

This report begins by discussing the primary corrosion damage mechanisms which occur at thermal power stations, then it moves on to describe expert systems in general which leads to a discussion of the CORALL expert system package. Finally, an example of a diagnostic session with CORALL is presented and concluding remarks are given.

2.0 CORROSION PROCESSES IN THERMAL POWER GENERATING STATIONS

There are three types of fossil-fired power plants. The most common plant is the pulverized coal-fired steam power plant, which may be used either as a baseload plant (where it runs continuously at capacity except for scheduled maintenance outages) or for intermediate loads between the steady baseload and higher loads needed daily. Gas combustion turbines are used for peak loads that occur for an hour or two each day. Combined cycle plants consisting

of gas combustion and steam turbines are generally intended for baseload service, although they must also be capable of sustaining intermediate-load service.

The fossil-fired plants are fuelled by natural gas, oil, and coal. Natural gas is generally clean and does not constitute a corrosion threat, unless firing is substoichiometric for reducing NO_x emissions. Oil can be corrosive to boilers if it contains vanadium and alkali metal impurities: these produce liquid vanadium oxides or alkali sulfates, both of which are highly corrosive to boiler tubes in the combustion chamber or hot-gas passages. Coal can also contain such impurities as sulfides and chlorides which can be extremely corrosive.

Each component at the complex power plant system possesses its unique corrosion problems due to: attack by service environment (high temperature, aggressive gases and liquids, erosion, vibration, mechanical stresses, etc.), human error, and incorrect and inconsistent application of ameliorative measures.

Steam Power Plant consists of three heat transport circuits: fuel-air, water-steam, and condenser cooling. In the fuel-air stream, the fossil fuel is burned in air, transfers its heat to a series of heat exchangers, is cleaned of particulate matter, may be scrubbed of sulfur oxides, and exits through the stack. In the water-steam circuit, clean feedwater is converted into superheated steam in a boiler, which expands through a series of turbines, converting its heat into mechanical energy, and is condensed, conditioned, pumped, and heated as feedwater back into the boiler. In the condenser-cooling stream, cold water is passed through the condenser and can be recirculated if a cooling tower is used or is returned back to the source of the cooling water.

The power plant equipment is usually divided into: boiler (steam generator) and auxiliaries. The fuels are combusted in a boiler constructed of water walls consisting of vertical or spiral steel tubes, welded together. The boiler feedwater rises in the water walls and is heated by the combusted fuel. The generated steam is separated from the boiler water which is returned to the bottom of the water walls through downcomers. The saturated steam is superheated by passing through banks of tubes exposed to the flue-gas stream. In supercritical boilers, the boiler pressure is above the critical point, and the liquid becomes superheated vapour without undergoing a phase change. The feedwater is conditioned to be slightly alkaline, but the fluid in the boiler may become acidic or caustic, depending on the nature of impurities and/or treatment chemicals, and presence of corrosion deposits and flow interruptions. If acidic conditions develop, the corrosion of steel boiler tubes is very rapid and the hydrogen evolved in the process is absorbed by the steel and causes hydrogen embrittlement. Under caustic conditions in deposits, the metal wastage of the steel boiler tubes is also very rapid and leads to caustic gouging. Overheating and excessive internal scaling in water walls may occur if boiling undergoes departure from nucleate boiling conditions.

The superheaters and reheaters are subject to steam oxidation with subsequent scale exfoliation from steam exposed surfaces. Hot corrosion and fly-ash erosion can become problems on the fireside surfaces.

The superheated steam leaves the boiler through heavy wall pipes and enters the high-pressure stage of turbine generator where it expands. Then it returns to the boiler for reheating before entering the intermediate-pressure turbine stage for a second expansion. After one or two expansions and reheatings, the steam enters the low-pressure stage of the turbine.

The dry steam is non-corrosive in the high or intermediate-pressure turbines except when condensation of solid sodium hydroxide (NaOH) occurs. However, when expansion of the steam in the low-pressure turbine reaches the point of initial condensation, high concentration of chloride and sulfate salt solutions may deposit. The concentration of these salts in steam condensate may be a million times higher than in the steam. Thus, the permissible impurity levels in the feedwater must be maintained in parts per billion in order to protect the low-pressure turbine. The condensate solution is often acidic as a result of evaporation of ammonia (NH_3) from the feed-water treatment process. In addition, during shutdowns, oxygen and carbon dioxide (CO_2) may dissolve in the acidic deposits on the turbine blades, leading to pitting with resulting loss of up to 90% fatigue strength. Measures which can be taken include: using blades designed to be strong enough to operate with pitted surfaces, periodic blade cleaning, maintaining the steam purity to avoid corrosive salt deposition, using more corrosion resistant low-pressure turbine blade materials (such as titanium alloys), or protecting 12% Cr steel blades with corrosion-resistant coatings.

Corrosion damage which can occur in the condenser include: sulfide-contaminated cooling water (seawater or brackish water) attacking copper-base tubes or tubesheets, pitting or crevice corrosion under deposits or barnacles or between tubes and tubesheets. However, the primary concern with condensers is in leakage of seawater or contaminated cooling water into the water-steam circuit which operates below atmospheric pressure. This in-leakage results in accelerated corrosion of boiler tubes and turbine components.

In the flue-gas handling equipment it is important to maintain the flue gas temperature above its dew point in order to avoid the deposition of sulfuric acid (H_2SO_4). Accelerated corrosion can also occur at areas where the hot flue-gas contacts cold surfaces.

Corrosion processes which occur in the steam power plants are summarized in Tables 1 and 2.

Gas combustion turbines consist of compressor, combustion chamber and turbine generator. The inlet air is compressed in a compressor, reacted with fuel in a combustion chamber, and directed at stationary airfoil vanes and through rotor blades or buckets constituting the turbine stage. Thus, the entire fuel and air input passes through the gas turbine. Any corrosive impurities present in either fuel or air will affect the high-temperature components, primarily the combustor, nozzle diaphragm, and turbine. Although the principal threats are oxidation and hot corrosion, the compressor components are susceptible to general and pitting corrosion due to condensation.

Corrosion processes which occur in the gas combustion turbines are summarized in Table 1 and 2.

Combined cycle power plant consists of gas turbine and a steam power plant. The gas turbine is used as a high-temperature topping cycle whose exhaust gas enters a boiler, which raises steam to operate the steam turbine and generator. To a large extent, corrosion problems in the combined cycle are simply the sum of the corrosion problems in the gas turbine and the steam power plant. Control of impurities in the inlet air and fuels reduces the corrosion damage.

3.0 EXPERT SYSTEMS

3.1 General Description

An expert system is a type of artificial intelligence program that emulates the interaction a user might have with a human expert on a subject area. Expert systems can be developed for any problem that involves a selection from among a definable group of choices where the decision is based on logical rules. The rules can involve relative probabilities of a choice being correct. Any area where there is a person or group of persons that have special expertise needed by others is a possible area for expert systems. Anything from identification of biological specimens, to automating complex regulations, to aiding customers in selecting from among a group of products, to automated user assistance is possible.

Expert systems deal with knowledge rather than data and the files they use are often referred to as knowledge bases. The rules that the program uses are IF-THEN type rules. A rule is made up of a list of IF conditions (normal English sentences) and a list of THEN conditions (more sentences) or statements about the probability of a particular choice being the appropriate solution to the problem. The computer determines what additional information it needs and how best to get this information. If possible, the program will derive information from other rules rather than asking the user. This ability to derive information allows the program to combine many small pieces of knowledge to arrive at logical conclusions about complex problems.

The final goal of an expert system is to select the most appropriate solution to a problem based on the data input by the user. If more than one solution is possible, the program could provide a list of the possible solutions arranged in order of probability.

TABLE 2

CORROSION PROCESSES WHICH OCCUR IN STEAM TURBINE GENERATORS AND AUXILLARY EQUIPMENT

CORROSION PROCESS	CONDENSERS	DEAERATORS	FEEDWATER HEATERS	STEAM TURBINES	GENERATORS	FLUE-GAS HANDLING SYSTEM	ASH HANDLING SYSTEM
Scaling and plugging							•
Dew-point corrosion						•	
Oxidation				•			
SCC-low cycle fatigue				•			
Erosion				•		•	
Pitting			•	•		•	
Crevice corrosion and/or under deposit corrosion			•	•		•	
Exfoliation			•				
Snake skin formation			•				
Corrosion fatigue		•		•			
SCC		•	•	•	•	•	
Erosion corrosion	•	•	•	•			•
General corrosion		•	•			•	
Crevice corrosion and/or pitting	•						
Dealloying	•						
Sulfide attack	•						
Galvanic corrosion	•			•			
Condensate corrosion	•		•				
Environmental cracking	•						

TABLE 1

CORROSION PROCESSES WHICH OCCUR IN BOILERS

EQUIPMENT	CORROSION PROCESS															
	FATIGUE		EROSION				FIRE-SIDE CORROSION				WATER-SIDE CORROSION				STRESS RUPTURE		
	Corrosion	Thermal	Vibration	Coal particle erosion	Sootblower	Falling slag	Fly ash	Oil ash	Coal ash	Waterwall	Low temperature	SCC	Oxygen pitting	Hydrogen damage	Caustic corrosion	Dissimilar metal welds	High temperature creep	Short-term overheating
Inside cyclone type coal burner				•														
Waterwall below burner level	•	•				•				•								
Waterwall at burner level	•				•					•				•	•			•
Waterwall above burner level	•	•			•					•				•	•			•
Economizer at feed water inlet	•	•			•						•		•					
Economizer at tube bends	•						•											
Economizer at flue gas inlet					•		•						•					
Superheater/reheater in radiant circuits		•	•					•	•			•	•			•	•	•
Superheater/reheater in convection circuits	•	•	•		•		•					•	•			•	•	•

TABLE 3

CORROSION PROCESSES WHICH OCCUR IN GAS COMBUSTION TURBINES

		CORROSION PROCESS		
		General corrosion and/or pitting	Hot corrosion at temperatures above 760°C	Hot corrosion at temperatures below 760°C
EQUIPMENT	Compressor blades & disks	•		
	Turbine blades & vanes		•	•

3.2 Benefits and Risks

Expert systems offer the following benefits:

- The knowledge about a limited domain is captured in the detail required for machine logic processing; a good knowledge representation will identify areas where the knowledge is uncertain or incomplete; areas for further research become clearly defined and the experiments to be performed are readily apparent (sharpening the expert).

- Human experts can be distracted or rushed and led to incorrect or inconsistent deductions; the expert system will always apply the same logic and give consistent results; the results will be correct if the rules are; when the expert system cannot arrive at a conclusion, it refers the user to the human expert (best knowledge base always gives best conclusion).

- All conclusions reached by the expert system are justified by inspectable rules; the human expert is freed from remembering all the details of the justification: this is a great time saver in areas where justification is repeatedly requested for slightly different inputs; in cases of disagreement among experts, the knowledge base challenges other experts to point out errors or to generate a correct rulebase (public thinking tool).

- With appropriate help facilities, an expert system can become an excellent tutor for transferring knowledge from an expert to his successor; this provides a company with some measure of protection against loss of expertise through attrition (preservation of knowledge).

- Non-specialists have access to expert knowledge if the expert is not available; problems that are well understood can be solved by anyone who has access to the expert system, this frees the expert from repeatedly executing the same task so that he can concentrate his efforts on acquiring new knowledge (efficient use of manpower.)

The risks involved in expert systems are the same as those associated with any computer program. The conclusions arrived at by an expert system may be wrong if the rules are incorrectly written and/or when the data entered by the user is wrong. Although CORALL is designed to guard against misinterpretation, conclusions should be treated like any conclusions of a single expert. A second opinion is recommended if an incorrect conclusion entails great risks.

3.3 The Expert System Shell Used

A program used to build an expert system is usually called an *expert system shell.* EXSYS[1], one of the many shells available, was used to create the expert system described in this paper. EXSYS is a generalized expert system development package. Expert systems can be developed with EXSYS for any problem that involves a selection from among a definable group of choices where the decision is based on logical rules. The rules can involve relative probabilities of a choice being correct.

Expert systems developed with EXSYS will ask the user questions relevant to a subject. The user answers by selecting one or more answers from a list by entering a numeric value. The computer will continue to ask questions until it has reached a conclusion. The conclusion may be the selection of a single solution or a list of possible solutions arranged in order of likelihood. The computer can explain, in English, how it arrived at its conclusion and why.

Expert system shells, such as EXSYS, coupled with the advance in micro-computer technology means that expert systems can be effectively built, installed on personal computers, and used by all who may need the assistance at low costs.

4.0 CORALL Expert System Package - Diagnosis of Corrosion Damages in Thermal Power Generating Stations

The CORALL expert system package was developed for use by electric utility and power plant personnel during investigations into the cause of corrosion damage. It is intended to assist their efforts to recognize and identify a basic damage mechanism that can produce the type of damage under investigation.

The acceptance of an expert system depends on the credibility of its knowledge base. In the conceptual design of CORALL, two criteria were established for selecting the main source for the factual portion of the knowledge base. The facts should have been: (i) published in public domain so that their reliability could be judged; and (ii) accepted by the practising experts in the area of corrosion damage analysis.

The "Corrosion in Fossil Fuel Power Plants" review section in the ASM Metals Handbook[1], and the "Manual for Investigation and Correction of Boiler Tube Failures" by the Electric Power Research Institute (EPRI)[2], met both criteria and were chosen to be the factual framework for CORALL.

The CORALL knowledge base was constructed around basic corrosion damage mechanisms, described in Section 2, which can independently or jointly bring a failure into being. The damage mechanisms can be determined, with a high degree of certainty, from plant type, location of the damage, type of fuel used, type of metal used, and characteristic appearance parameters. The relationships between corrosion damage mechanisms and these factors are well established with very little ambiguity.

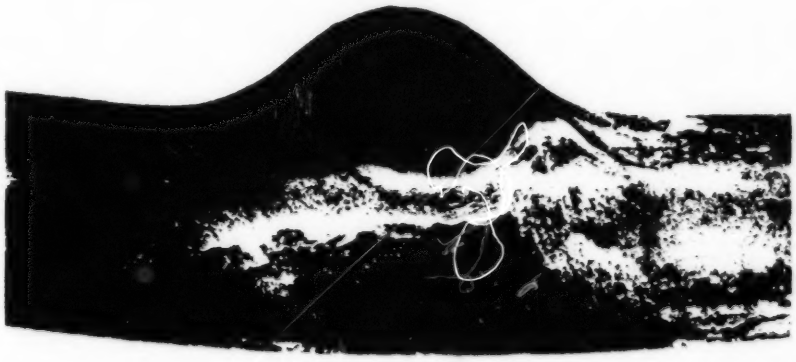
This knowledge is organized into a decision tree structure incorporating the facts from the EPRI Manual and the ASM Metals Handbook and heuristic components contributed by the developers of CORALL. The facts are expressed in the form of production rules using the EXSYS expert system development package. CORALL combines three separate expert systems: COREXYS™, CORAUX, and CORGAS to provide a corrosion damage diagnostic system for all types of fossil fuel power plants. The COREXYS™ expert system aids investigations into the cause of boiler tube failures, CORAUX contains information on causes of corrosion damage in steam turbine generators and auxiliary equipment, and CORGAS helps in determining the cause of corrosion damages in gas combustion turbines.

Expert systems developed with EXSYS, such as COREXYS™, CORGAS, and CORAUX, can be run on any IBM PC, XT, AT or compatible computer which has at least 256 K of RAM, one single sided disk drive, and uses DOS Version 2.0 or higher. An easy to follow User's Guide accompanies the software and gives more details regarding system requirements. The guide describes, and explains how to use, all the features of CORALL (running, printing, displaying graphics, etc). The CORALL User's Guide can also be used as a reference and/or learning tool since it includes descriptions of all the basic corrosion damage mechanisms used in the program. This User's Guide together with the floppy disks make up the CORALL expert system package.

Use of CORALL expert system package does not eliminate the need for a thorough metallurgical analysis during the failure investigation since such an analysis is essential in many cases to confirm or ascertain the responsible damage mechanisms.

5.0 EXAMPLE OF A DIAGNOSTIC SESSION

For the purpose of demonstrating a diagnostic session with the CORALL expert system, a boiler tube failure in the following Figure[4] was chosen.



This tube failure occurred in a superheater convection circuit of a pulverized coal fired boiler and is characterized by the following parameters, determined through a visual observation:

- significant tube deformation in the form of metal elongation and reduction in wall cross-section, considerable swelling and increase in tube's diameter,
- rupture shape is fish-mouth like in appearance,
- rupture edge is thin, knife like,

Beginning at the main menu,

Screen 1

EXPERT SYSTEMS TO DIAGNOSE CORROSION DAMAGE IN FOSSIL FIRED POWER PLANTS

Select the power plant type

1. gas combustion turbines
2. steam power plant (steam boiler and turbine)
3. combined cycle (gas turbine, steam boiler and turbine)
4. EXIT

Selection _____

The user selects #2 (steam power plant). CORALL then wants to determine the equipment that has been damaged.

Screen 2

The equipment damaged by corrosion is the

1. boiler tubes
2. steam turbine generators or the auxiliary equipment
3. DONE

Since the component under investigation is a boiler tube the user selects #1. If #1 is selected, the expert system COREXYS™ is invoked.

First, the COREXYS™ expert system requests information on the failed tube location. The user is asked to choose from nine specific locations shown in the third screen.

Screen No 3

The boiler tube failure locations is:

1. waterwall below burner level
2. waterwall at burner level
3. waterwall above burner level
4. economizer at feed water inlet
5. economizer at tube bends
6. economizer at flue gas inlet
7. superheater/reheater in radiant circuits
8. superheater/reheater in convection circuits
9. inside cyclone type coal burners

Enter numbers of appropriate value(s), WHY for information on the rule being applied or ,<H> for help.

The user knows that the boiler tube failure location is superheater in convection circuits and enters #8 and ENTER.

Then the system requests information on the shape of tube rupture on the fourth screen.

Screen No 4

The tube rupture shape is:

1. pin-hole resulting from pitting on internal surface
2. fish-mouth opening
3. crack(s)
4. other

Enter number(s) of appropriate value(s), WHY for information on the rule being applied or <H> for help.

Enter number(s) of appropriate value(s), WHY for information on the rule being applied or <H> for help.

From visual observation the user can easily establish that the rupture shape is a fish-mouth like opening and enters #2 and ENTER.

The system automatically determines what to ask next to diagnose the tube failure mechanism. In this case information regarding the rupture edge is required.

Screen No 5

The tube's rupture edge is:

1. thick and oxide coated
2. thin

Enter number(s) if appropriate value(s), WHY for information on the rule being applied or <H> for help.

Since the tube rupture edge is thin and knife-like, the user enters 2 and presses ENTER.

Based on the provided information, the system performs a diagnosis and determines the boiler tube failure mechanism and displays a
summary on screen six.

Screen No 6

SHORT-TERM OVERHEATING

Short-term overheating often results in boiler tube failures. These failures are experienced when a single incident or a small number of incidents expose the tube steel to excessively high temperatures (hundreds of degrees above design) to the point where deformation or yielding will occur. Overheating failures are often called "short-term" or "rapid" overheating failures to indicate that the period of high temperature exposure was relatively small compared to the total in-service life of the tube. Overheating failures can be experienced by either water-cooled turbine or steam-cooled tubing. Overheating develops from abnormal conditions such as loss of coolant flow or excessive boiler gas temperature.
These abnormal conditions are created by the following circumstances:

- Blockage of the tube internally,
- Loss of boiler coolant circulation or low water level,
- Loss of coolant due to an upstream tube failure,
- Over-firing or uneven firing of boiler fuel burners.

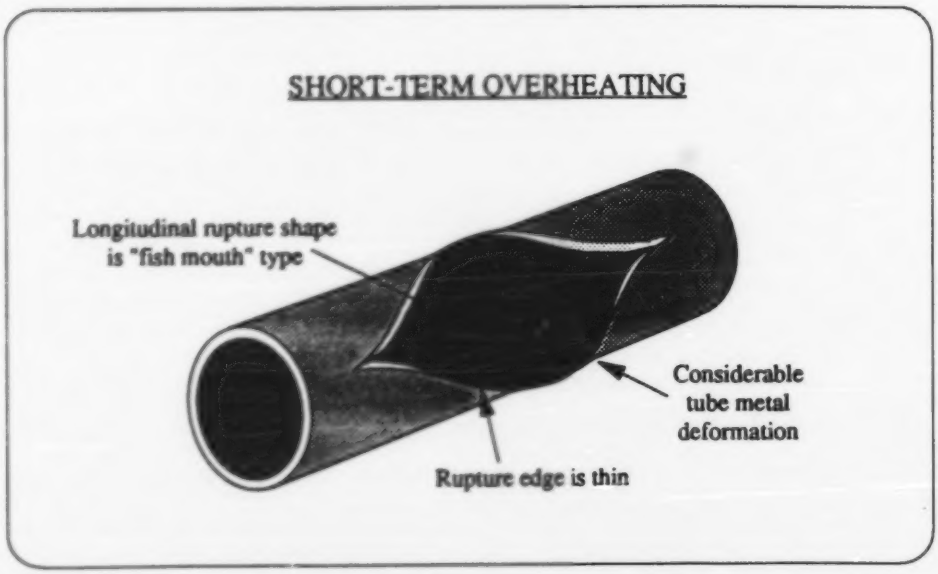
Short-term overheating can occur in steam-cooled and water cooled tubes at locations that:

- Have become plugged by debris, scale, or condensate from incomplete boilout,
- Have exposure to high heat transfer rates from improper firing of fuel burners,
- Have experienced low coolant flow due to poor circulation or upstream tube leak.

Short-term overheating produces considerable tube deformation in the form of metal elongation and reduction in wall area or cross section. A fish-mouth type longitudinal rupture with thin-edged fracture surfaces is typical for a ferritic steel when it has failed before reaching its upper critical temperature. Other appearances are possible depending on the material and the extent of the overheated portion of the tube.

If your computer has graphics capabilities, COREXYS™ will then display screen seven.

Screen No 7


SHORT-TERM OVERHEATING
Longitudinal rupture shape is "fish mouth" type
Considerable tube metal deformation
Rupture edge is thin

Hit any key to continue and a one line summary of the conclusion is shown. At this point enter 1 and press ENTER. The rule used to determine the conclusion is displayed in screen eight.

Screen No 8

RULE NUMBER: 39,
IF:

1. The boiler tube failure location is superheater/reheater in radiant circuits.
2. The tube rupture shape is fish-mouth opening and
3. The tube rupture edge is thin

THEN:

The failure mechanism is SHORT THERM OVERHEATING - Probability - 1

Input IF line number for info on how it was derived <H> for help or <ENTER> to continue.

6.0 SUMMARY

A rule-based system, to assist thermal power plant staff in recognizing and identifying basic causes of equipment corrosion damage, was developed. This micro-computer based software package is an essential tool for efficient analysis and resolution of equipment problems through correct determination of the failure mechanism which is necessary to establish root cause of the failure. The program allows consistent application of ameliorative measures to effectively mitigate routinely occurring equipment problems.

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